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REACTION WHEELS FOR KINETIC ENERGY STORAGE

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ABSTRACT

In contrast to all existing reaction wheel implementations, an order of magnitude increase in speed can be obtained efficiently if power to the actuators can be recovered. This will allow a combined attitude control-energy storage system to be developed with structure mounted reaction wheels.

Combining reaction wheels with energy storage wheels may seem an unlikely marriage between two elements with opposing requirements. This paper will show that they are not incompatible. The power required for control torques is a function of wheel speed but this energy is not dissipated; it is stored in the wheel. The I^2R loss resulting from a given torque is shown to be constant, independent of the design speed of the motor. What remains, in order to efficiently use high speed wheels (essential for energy storage) for control purposes, is to reduce rotational losses to acceptable levels.

Progress has been made in permanent magnet motor design for high speed operation. Variable field motors offer more control flexibility and efficiency over a broader speed range. Research necessary to reach the goal of efficient kinetic energy storage will have generic benefits to spacecraft attitude control systems and dynamic power systems. (See fig. 1.)

REACTION WHEELS for ENERGY STORAGE

AC/ES

- + REGENERATIVE TORQUE CONTROL
- + I^2R INDEPENDENT OF SPEED

MOTOR TECHNOLOGY

- + IRONLESS ARMATURE
- + PERMANENT MAGNETS
- + VARIABLE FIELD-CONSTANT VOLTAGE

Figure 1

REACTION WHEELS FOR KINETIC ENERGY STORAGE

Energy storage in flywheels has had a long and successful history in machines as simple as grandmother's spinning wheel to current automotive engines. It has recently been studied and found potentially competitive for applications in which the desired output is electrical as an alternative to electrochemical batteries. Rotating machinery has not had a significant role in aerospace power systems, whereas attitude control systems have used flywheels for stabilization and control since the early days of space flight. Combining these functions could potentially reduce the weight of two of the heaviest elements in both of these systems. Power used for attitude control has not been recovered in the past. Brushless DC motor drives make it possible to recover energy previously lost, improving system efficiency.

Merging these two subsystem functions and recovering energy used for control radically change the tradeoffs used to size and set the speed limits on reaction wheels. It will be shown that several improvements in technology have the effect of raising the optimum design speed of reaction wheels with a consequent reduction in control system mass. Likewise, the further evolution of wheel technology necessary to make flywheels competitive with batteries will have a beneficial effect on all future attitude control systems.

Historically, reaction wheels have been low speed devices. They are generally operated at nominally zero speed and are able to store momentum by rotating in either direction. The maximum speed is set by the cyclic momentum expected in one orbit. The rotational motion of the wheel is a

mirror image of the motion of the spacecraft (or what that motion would be if unopposed). The amplitude of the angles, rates, and accelerations are proportional to the ratio of the inertia of the wheel to inertia of the spacecraft about the axis of control. The stored momentum is the product of wheel inertia and angular rate. Therefore, a tradeoff is routinely run between Reaction Wheel Assembly (RWA) weight and power as a function of maximum speed to find a minimum effective weight which will meet the mission momentum requirement. (See fig. 2.)

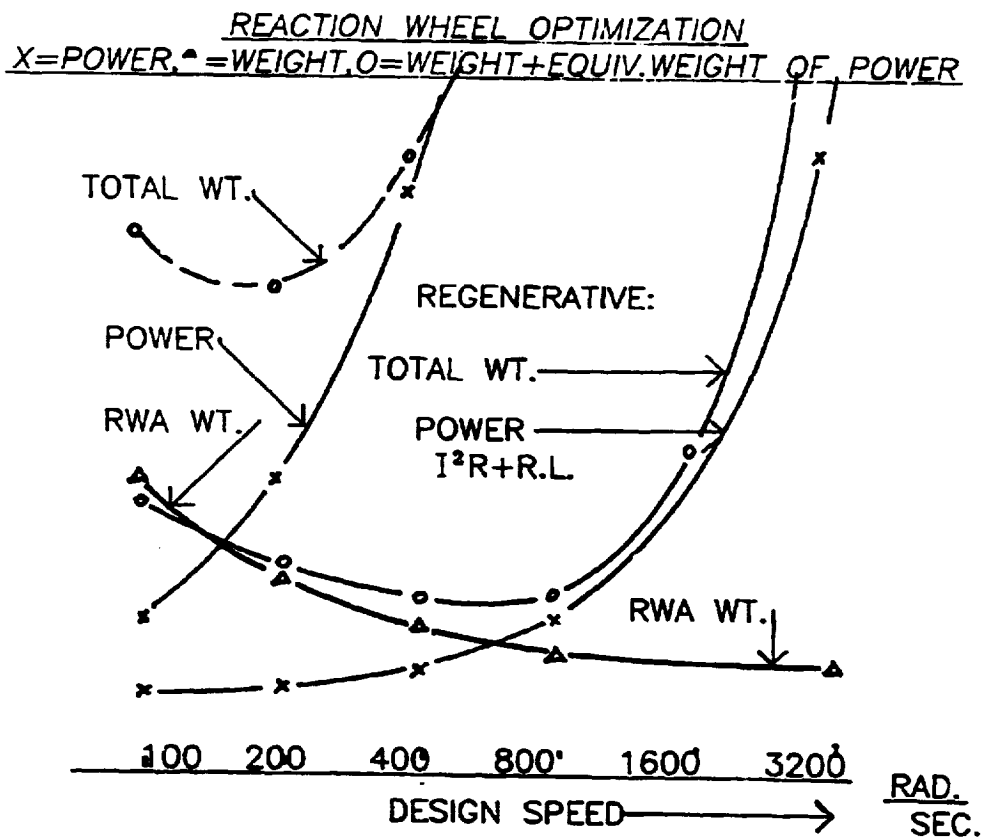


Figure 2

This proportionality between power and maximum speed is based on the physical law relating power to speed and torque (figure 2). The motor constant K_T , torque per ampere, is equal to K_V , volts per rad/sec. We cannot change these physical relationships but we note that this energy is not dissipated, it is stored in the wheel. In the case of a combined attitude control/energy storage (ACES) system, we have simply transferred energy from one storage element to another where it remains available to the power system. Since reaction wheel control handles cyclic torques, the wheel will be called on to slow down as often as to accelerate. The drive must be a motor/generator to efficiently recover the stored energy and transfer it to the spacecraft electrical load. The permanent magnet dc motor is an efficient transducer. It behaves equally well as a generator and as a motor. This power recovery has not generally been implemented in spacecraft control systems because the energy was relatively small and the voltage variation was 100 percent, making efficient recovery very difficult. For high speed energy storage wheels, the energy involved will be larger and the voltage variation much smaller.

The efficient transfer of power requires a careful look at the amount of power dissipated in the process. As we have seen earlier, the motor constant K_T decreases in proportion to the increased no-load speed of the motor. At first glance, an order of magnitude increase in the current to produce a given torque looks alarming, recognizing that I^2R is the power dissipated.

However, (figure 3) the number of turns (armature conductors) necessary to achieve K_V and K_T are lower by the same proportion. Also, if the motor in question is the same size, the diameter of the conductors can also be proportionally increased. Therefore, R decreases as fast as I^2 increases and the internal dissipation is the same for all design speed ranges.

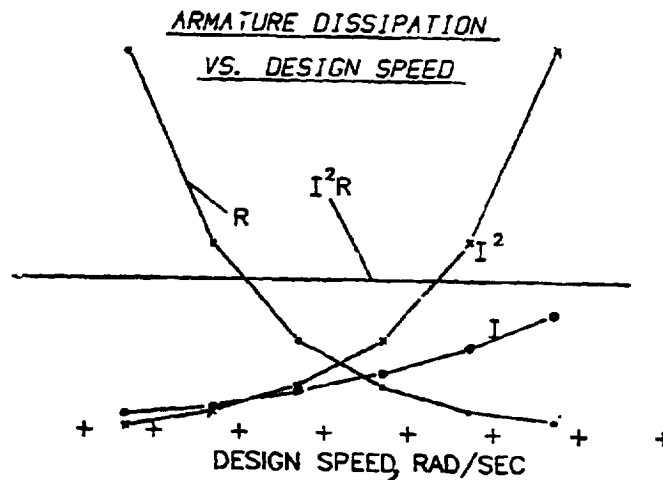


Figure 3

A more difficult challenge is posed by the rotational losses. At peak efficiency the rotational losses are equal to the $I^2 R$ losses (figure 3). Furthermore, these are not all linearly related to speed. There are components which are speed independent, such as hysteresis in motor laminations, and some which increase faster than the square of the speed such as windage. It is necessary to isolate and eliminate as many sources of parasitic loss as possible if efficient high speed operation is to be achieved⁽¹⁾. There follows a list of losses not associated with power into or out of a dc motor generator (see fig. 4):

ROTATIONAL LOSSES

SOURCES: _____ SOLUTIONS: _____

BRUSHES,
 MECH. _____
 ELEC. _____ POWER FETS
WINDAGE, _____ VACUUM
"CORE" LOSSES,
 HYSTERESIS _____ IRONLESS ARMATURE
 EDDY CURRENTS _____
ARMATURE,
 EDDY CURRENTS _____ "LITZ" WIRE
 CIRCULATING CURRENTS _____ "WYE" WINDING

Figure 4

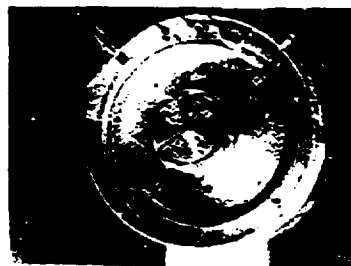
Electronic commutation has eliminated the mechanical drag torque associated with carbon brushes. There are electrical losses due to leakage currents in power switches and diodes, logic circuit power drain, and rotor position sensors. All of these occur independent of the power demand on the motor/generator. They are also independent of the operating speed of the motor and will not be considered further here.

Windage loss is extremely speed dependent; but the solution is straightforward. Reduction of enclosure pressure to 10^{-5} torr can make this loss negligible over the entire speed range.

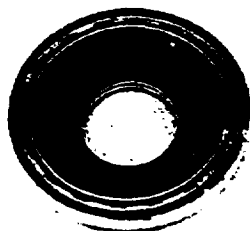
Bearing drag torques for mechanical bearings have both coulomb and viscous components. The power loss is therefore proportional partly to speed and partly to the square of wheel speed. Magnetic bearings offer somewhat lower torques having the same effects due to hysteresis and eddy currents. Treating magnetic bearing torques adequately would require a full discussion in another paper. For the purpose of this discussion, let us assume that the bearing torque loss can be held to small enough levels so as not to drive the choice of operating speed.

For conventional dc motors, the hysteresis and eddy current losses are much larger than bearing losses for the power and torque levels required for either energy storage or reaction wheel control. These losses occur in the laminated magnetically soft iron into which the armature conductors are wound. Although the potential of newly developed amorphous steel alloys, such as Metgas (a trademark of Allied Corp.), have not been fully explored, the power losses of this type of motor would likely be prohibitively high at the upper end of the speed range.

Fortunately another dc motor construction is available. These so-called "ironless armature" dc motors have the armature conductors in the magnetic air gap⁽²⁾ (figure 5).



MOTOR ARMATURE (IRONLESS)
& MAGNETIC BEARING STATOR



PERMANENT MAGNET SmCo₅ MOTOR ROTOR
& MAGNETIC BEARING SUSPENSION RING

Figure 5

The entire "iron" and permanent magnet field assembly is on the rotor and there is no relative motion between it and any stationary iron. Therefore, there is no hysteresis loss. There remains eddy current loss within the armature conductors themselves, but even this can be reduced by known methods such as subdividing each conductor into finer strands ("litz" wire)⁽³⁾. Further gains can be expected by pole shaping to make the field pole flux vary sinusoidally since the flux gradient creates the eddy currents. Neither of these techniques drastically affects the performance or sizing of the motor. Therefore, very high efficiency, high speed motor design can be approached with confidence when the necessary analytical and experimental resources are applied.

There are a few other sources of parasitic power losses such as circulating currents within the armature windings and eddy currents in various structural and mechanical parts which require careful engineering attention because they are generally ignored in less demanding applications.

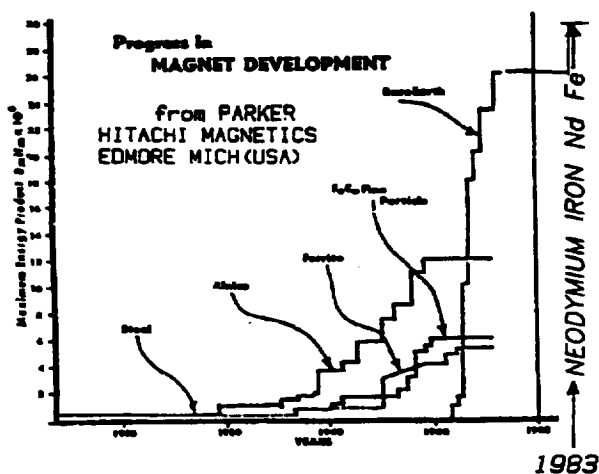


Figure 6

Permanent magnet motors have improved significantly in the past 25 years (figure 6) and each of these steps has allowed efficient operation at a higher speed regime. Higher speed puts more energy into a smaller lighter package. This has a visible impact in attitude control technology—the NOAA series of spacecraft utilize brushless dc reaction wheels with a no-load speed of 10,000 RPM. Neither ironless armature motors nor magnetic bearings have yet been applied to flight spacecraft systems by American aerospace manufacturers. In spite of many feasibility demonstrations, the required depth of engineering analysis and design has not been applied. However, given the technology program needed to accomplish the kinetic energy storage task, generic improvements in attitude control systems will result.

All of the earlier discussion focused on permanent magnet motors. Would field motors offer greater control flexibility, the ability to vary the peak of the efficiency point to match the load, and produce constant voltage over a range of speeds. (See fig. 7.)

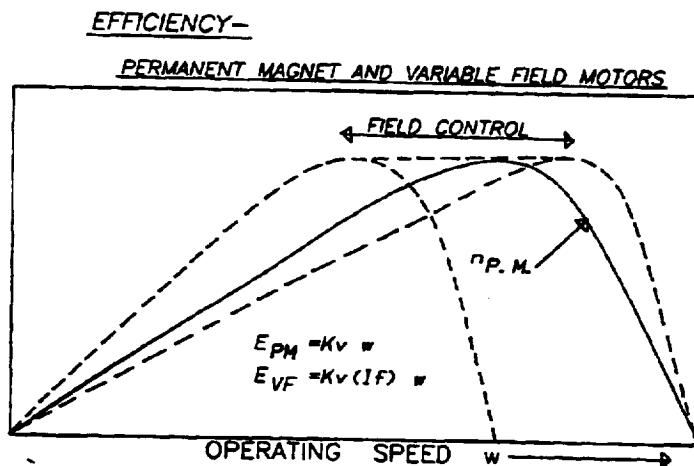


Figure 7

This technology was explored briefly in the 1960's and is applicable to combined energy storage and attitude control systems. The value of wound field motors increases at higher power levels now being considered. NASA owns the patents on this design approach^(4,5). To improve balance stability both the field and the armature windings are on the stator. The rotor is entirely a magnetically soft ferro-magnetic alloy, which has the requisite strength properties for use on energy storage wheels. Since the field flux is induced into the rotor via an auxiliary airgap(s), the magnetic suspension can be integrated into the motor design with a sizeable weight savings since they utilize a common "iron" path. Integration of these two prime functions adds a significant challenge to the engineering design task. The payoff is a vastly superior product.

In conclusion, the GSFC is already operating reaction wheels in space with good reliability at speeds as high as 10,000 RPM. The technological path which will allow quadrupling this speed to make kinetic energy storage competitive with electrochemical systems has already been charted. If the decision is made to proceed with development and use of ACES, a significant advance will be achieved in two primary spacecraft subsystems. If the United States does not meet this challenge, someone else will; the Europeans⁽⁶⁾ and the Japanese⁽⁷⁾ are already proceeding with developments of energy storage flywheels.

Efficient recovery of the energy stored in a flywheel is implicit in a kinetic energy storage system. When this mode of operation is incorporated into the reaction wheel sizing and speed selection tradeoffs, much different results are obtained.

The technological development program to make efficient reliable energy storage wheels will have substantial intermediate benefits in attitude control and dynamic power systems generally. Power efficient lightweight high-speed control and momentum storage wheels will improve spacecraft "bus" performance, increasing payload mass fraction and available power for instruments. Combining the functions of control actuators and energy storage as in ACES focuses the technology on two of the more massive elements in spacecraft and can be of particular value in large scale long-life systems where resource sharing, distributed control, and unlimited cycle life are essential.

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